IMPROVING THE AIR MOBILITY COMMAND'S AIR REFUELER ROUTE BUILDING CAPABILITIES

THESIS

Tanya E. Kannon, Captain, USAF

AFIT-ENS-14-M-14

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, the Department of Defense, or the United States Government.

AFIT-ENS-14-M-14

IMPROVING THE AIR MOBILITY COMMAND'S AIR REFUELER ROUTE BUILDING CAPABILITIES

THESIS

Presented to the Faculty
Department of Operational Sciences
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Operations Research

Tanya E. Kannon, B.S., A.A.S.
Captain, USAF

March 2014

AFIT-ENS-14-M-14

IMPROVING THE AIR MOBILITY COMMAND'S AIR REFUELER ROUTE BUILDING CAPABILITIES

Tanya E. Kannon, B.S., A.A.S.
Captain, USAF

Approved:

//signed//	14 Feb 2014
Sarah G. Nurre, PhD (Chairman)	Date
//signed//	14 Feb 2014
Raymond R. Hill, PhD (Member)	Date
//signed//	14 Feb 2014
Jeffery D. Weir, PhD (Member)	Date

AFIT-ENS-14-M-14

Abstract

We consider the problem of routing an aircraft (receiver) from a starting location to a target and back to an ending location while maintaining a fuel level above a predetermined level during all stages of the route and avoiding threat and no-fly zones. The receiver is routed to air refueling locations to refuel as required. The development of the network requires the processing of threat and no-fly zones to create the set of nodes that includes the bases (starting and end locations), the targets, and air refueling locations in addition to the restricted zone nodes. We develop a greedy heuristic that builds the route using arc paths and the on board fuel level to determine the termination of each sequential arc path. Post processing of the routes reduces the fuel remaining on board by shifting the time at target or reversing the route. The results from the greedy heuristic are compared to the results from the current methodology and show that the heuristic requires less time to produce routes that require less fuel.

To my husband who patiently listened and helped tremendously even when he said he didn’t have a clue what I was talking about

Acknowledgments

Many thanks to Mr. Jim Donovan, Headquarters Air Mobility Command / A9, for the problem, data set, and guidance on current methodology.

Thanks to Dr. Hill for stepping back into the optimization world with me, LTC Lunday for giving me the opportunity to think about the problem in a completely different way, and Dr. Nurre for embracing the problem and helping me despite my initial reluctance.

Tanya E. Kannon

Table of Contents

List of Figures

List of Tables

IMPROVING THE AIR MOBILITY COMMAND'S AIR REFUELER ROUTE BUILDING CAPABILITIES

I. Introduction

1.1 Background

Air Refueling consists of one aircraft transferring fuel to other aircraft while all are in flight. The aircraft that transfers the fuel is a tanker while those aircraft taking on fuel are known as receivers [19]. The Air Force uses air refueling to extend the range of receiver aircraft and reduce the total number of aircraft (including tankers and receivers) needed to complete a campaign. Headquarters Air Mobility Command (HQ AMC) determines the appropriate number of tankers for the Air Force to maintain and recommends the number of tankers required to meet the needs of a specific campaign.

Tanker redeployment recommendations are based on data from simulation models run at Headquarters Air Force. The Air Force uses these models to drive policy decisions and force structure. These simulation models make assumptions that require the results to be refined. The Synthetic Theater Operations Research Model (STORM) is one of the simulation models used. In STORM, a receiver is considered refueled based on their proximity to a "cloud" of fuel. Determination of the position of the tanker inside the "cloud" as well as adjusting the mission details of the receiver are necessary before determining the actual route of the receiver.

The current method used by HQ AMC makes these mission detail adjustments to the STORM output and determines the necessary tanker requirements by building a route for each mission and calculating the total number of refuelings required. That number is then used to derive the tanker requirements for all missions in a campaign.

The HQ AMC method starts by determining the route for each mission with no consideration for fuel usage. It then calculates the number of refuelings required by dividing the cost of that route by the amount of fuel available on board the receiver above the reserve fuel amount. The needed refuelings are then assigned to aerial refueling locations with the required route changes made by hand and any scheduling deconfliction resolved manually.

Multiple complications exist for each route. The location of the bases and targets can be in an area with threat zones (from missile sites) or no-fly zones. Threat zones can be flown through but only on combat missions. No-fly zones cannot be flown through. Fuel levels cannot fall below a predetermined reserve amount.

It is assumed that all tankers in the air can refuel all receivers and that all receivers complete their mission with the given specifications (fuel burn, time at target, etc). Tankers are located in a known position and receivers orbit with tankers to complete fuel offload. All receivers must arrive at a tanker with enough fuel on board to deviate to a missed refueling base if the refueling fails. The locations of the missed refueling bases are known at the start of the mission.

The receivers have a known take off location (that can be inside a restricted zone) and a known target location. The speed and fuel burn rate of receivers is a function of the mission and current location of the receiver. The time at target (TaT) is predetermined and may require refuelings to complete.

1.2 Problem Statement and Scope

This project formulates, defines, and prototypes a route builder to assist HQ AMC planners. The route builder's primary objective is to minimize the fuel required for the route while maintaining the required fuel levels throughout the mission. The secondary objective is to minimize the amount of fuel remaining on board the receiver (above the reserve fuel amount) at the end of the mission. The current project only focuses on the single receiver pre tanker scenario.

1.3 Contribution of Research

This project focuses on automating the route building process for HQ AMC by creating a greedy heuristic to build the routes while maintaining the required fuel levels.

1.4 Report Overview

Chapter 2 covers the previous work done relating to this research. Chapter 3 covers the data preprocessing and network creation. Chapter 4 covers the heuristic developed to minimize the fuel cost of the route. Chapter 5 covers the results of the heuristic as applied to sample missions. Chapter 6 covers expansions of the methodology to minimize the fuel remaining on board at the end of the route. Chapter 7 covers additional areas of focus for future work.

II. Literature Review

The problem addressed in this paper is an aircraft routing problem with restricted areas and fuel level considerations. This problem boils down to a constrained shortest path problem. The network being used is undirected and cyclic with obstacles that prevent full connectivity. Some nodes in the network allow for the fuel level to be reset (due to refueling) if the route cost will exceed the predetermined amount of fuel. The refueling can occur before the fuel level drops below the predetermined amount of fuel.

Ahuja et al. [1] provide a description of the shortest path problem and explains multiple exact solution methodologies. Most of the exact solution methodologies are variations of Djikstra's method which finds the shortest path through the network by finding the shortest path to each node in the network. Kannon et al. [13] use a non-polynomial extension of Djikstra's to solve the constrained shortest path with fuel limitations. The objective is to minimize the distance traveled.

Some aircraft routing problems involve scheduling multiple sorties and deconflicting air space such as in Desaulniers et al. [9]. Their focus is to maximize profits of flights scheduled to cover known legs with time windows, durations, and profits. Barnhart et al.[3] solve the problem of assigning flights to specific aircraft for a known set of flights. Barnhart et al. [2] cover multiple applications of scheduling and other operations research techniques to the world of air transit.

Some routing problems involve the creation of specific routes through air space with and without obstacles avoidance. Carlyle et al. [7] present a solution method for finding a shortest path through a network with ground based threats. Their method can also account for fuel limitations but only by limiting the fuel required for the mission. Bartholomew-Biggs et al. [4, 5] focus on a methodology to avoid obstacles while building the route with turning radius and network density their only limitations.

O'Rourke et al. [15] examine a traveling salesman version of aircraft routing in the unmanned aerial vehicle realm. The route for the network involves multiple sites that must be visited. They focus on a dynamic tabu search methodology. Harder et al. [10] expand on this work by adding additional side constraints while Kinney et al. [14] focus on improving the tabu search functions used in the routing tool.

Sundar and Rathinam [18] also study a traveling salesman version of the problem in the unmanned aerial vehicle realm. Their focus is on smaller vehicles that must visit all nodes and can refuel at any node.

Bush [6] examines at the refueling aspect of a point to point routing problem but focuses on finding the optimal location for the refuelings to occur under several different conditions. He also considers the complication of the spherical geometry required to plan air travel.

A network can be complicated by the existence of nodes that are intentionally not connected because some connections would intersect a restricted zone. By inscribing the restricted zones with new network nodes, the restricted zone can be avoided. Helgason et al. [11] describe a method in which obstacles are inscribed in triangles and a branch and bound algorithm is used to find the shortest path around using the vertices of the triangles. Choi et al. [8] expand on previous work done by Papadimitriou [16] to find an approximate route through a space with polyhedral obstacles. They focus on improving Papadimitriou's method for breaking up the edges of the obstacles into smaller segments.

III. Network Creation

To build a route to meet mission requirements, the network must be developed to include all applicable nodes and arcs. The existence of threat and no-fly zones complicates the development of that network. We start by processing the threat and no-fly zones then use the nodes and arcs associated with the generated restricted zone to create the remaining network arcs.

3.1 Problem Description

There is a set of missions M, each of which requires a route through a network from some take off location to some target and back to a landing location that minimizes the total fuel required for the mission. While at the target, the route accounts for the total time spent at target (TaT). Each mission $m \in M$ has a set of associated parameters (shown in Table 3.1) that are used for the route building algorithm. There are additional parameters associated with each mission that are used in the preprocessing of the data for the creation of the set of network arcs.

Table 3.1: Definitions of Parameters Provided for Each Mission

Parameter	Definition
$Mission\_Type_m$	Type of mission
$TOBase_m$	Take off base and location
$Land\_Base_m$	Landing base and location
$Target_m$	Target and location
$TOFuel_m$	Amount of fuel on takeoff, air refuelings refuel to this value
TaT_Fuel_m	Calculated fuel requirement for time at target (TaT)
$Reserve\_Fuel_m$	Minimum fuel level for receiver during mission

Let $G = (N, A)$ represent the network over which the route is built, where N represents the set of nodes and A represents the set of arcs. Within the set of nodes N, there are four subsets of nodes, bases B, targets T, air refueling locations AR, and the extreme points associated with each restricted and no-fly zone r, N^{RZ_r}. The set N^{RZ} contains the nodes $\in N^{RZ_r}\ \forall\ r$. Bases, B, are take off locations, missed refueling locations, and landing locations. Targets T, are the locations of the mission targets. Any node interior to the restricted zone is in T. The location of each node $i \in N$ is represented in latitude and longitude. Each node $i \in B$ also has an associated list of suitable receivers that can land at the base known as a missed refueling base (MRB) in the event of an aborted air refueling. Within the set of arcs A, there is one subset, A^{RZ}, that contains the arcs associated with the restricted zones.

Table 3.2: Definitions of Arc Parameters Common to All Missions

Parameter	Definition
$Start_{ij}$	Name, latitude, and longitude for node i
End_{ij}	Name, latitude, and longitude for node j
$Dist_{ij}$	Calculated distance along arc (i, j)
$Percent\_Combat_{ij}$	indicates percentage of arc treated as combat
$Type_{ij}$	Combat if $Percent\_Combat > 0$
$Refueler_{ij}$	Indicates arc (i, j) ends at air refueling location
$Base_{ij}$	Indicates arc (i, j) ends at base

Each arc $(i, j) \in A$ has the set of associated parameters shown in Table **??** which are the same across all missions. There are three additional parameters specific to each mission: $Fuel_{ij}$, the fuel required to travel arc (i, j), $Under\_Consideration_{ij}$, if an arc can be traveled based on the mission type, and $Fuel\_to\_MRB_i$, the fuel required to get to the nearest MRB from any node $i \in AR$. These parameters are calculated based on the receiver used in each mission.

3.2 Data Preprocessing

We generate the set of restricted zone nodes, N^{RZ}, around areas in the network map that are no-fly zones and threat zones. The threat zones can be flown through for specific mission types but any flight within a threat zone must be flown at combat speeds. A no-fly zone cannot be flown through. Any overlapping zones can be covered by one larger zone to minimize the size of N^{RZ}.

Figure 3.1 shows the provided threat and no-fly zones for a sample network. The blue circles show the threat zones and the no-fly zones are outlined in red. For the sample network, the no-fly zones cover the countries of Israel, labeled RZ_1, and Lebanon, labeled RZ_2, and the threat zones are based on two missile sites in Syria, RZ_3 and RZ_4. RZ_3 and RZ_4 overlap and can be covered by one large restricted zone. The two countries form one no-fly zone. The restricted zone area, RZ, is defined by the sets of boundary nodes, N^{RZ}, and the arc connections between them, A^{RZ} .

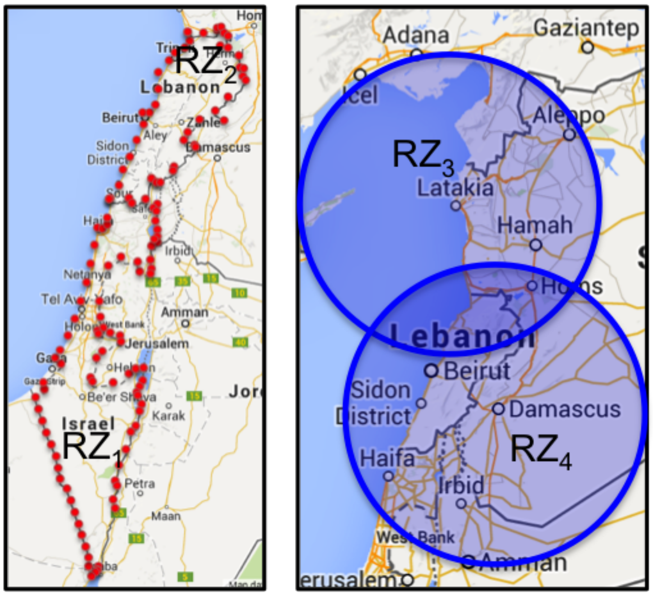

Figure 3.1: Example of Threat (SAM Sites in Syria) and No-Fly Zones (Israel and Lebanon) from Sample Scenario

N^{RZ} is created by processing the mapped threat and no fly zones. The threat zones are each inscribed in a hexagon with a radius 1.2 times larger than the radius of the circle. The convex hull of the overlapping hexagons is found (using the corners of the hexagon only) by applying a tool created by Pope [17]. The no-fly zones are processed using border points for the countries (from a KML file from Google Earth) using the same tool. A^{RZ} is the set of arcs of each of the convex hulls. Figure 3.2 shows the restricted zones after processing.

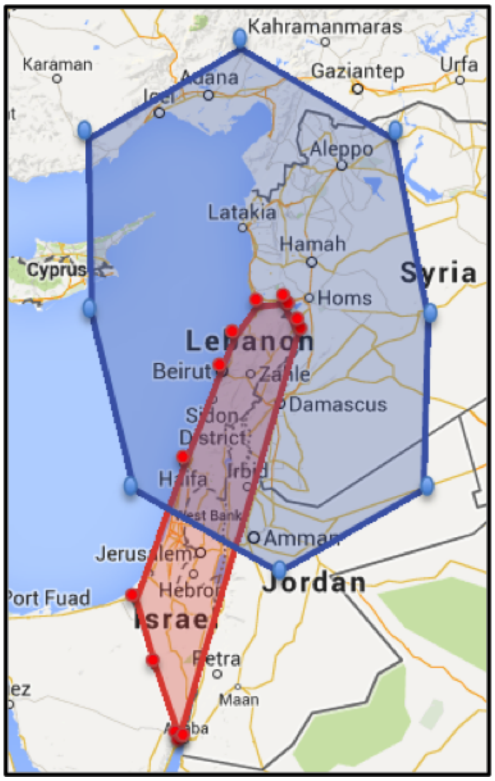

Figure 3.2: Example Restricted Zone After Determining Convex Hull of Countries and Inscribed Threat Zones

3.3 Arc Creation

The set of arcs A provides the set of feasible connections between all nodes in the network. When adding arc (i, j), its parallel arc (j, i) is also added. All nodes i and j in AR and T and B are fully connected provided i and j are not interior to a restricted zone and arc (i, j) does not cross the no-fly zone. All nodes in N^{RZ} have limited connections to other nodes. Any nodes in T have limited connections to other nodes if they reside within the restricted zone.

The set A is created using Algorithm 1 and the set A^{RZ}. The slope and intercept of each arc in A^{RZ} are calculated using Equations 3.1 and 3.2 using the latitude and longitude of node i, ϕ_i and λ_i, and node j, ϕ_j and λ_j. The intersection of each potential arc with each arc $\in A^{RZ}$ is found using Equation 3.3. If the intersection falls along both arcs between the network nodes and the arc in A^{RZ} connects two no-fly nodes, the arc is not allowed and is not created. If the intersection is between the network nodes and the arc is connecting restricted zone nodes, then the arc is created with $Type_{ij} = Combat$. If there is no intersection, the arc is created with $Type_{ij} = Cruising$.

$$Slope_{ij} = \frac{\lambda_i - \lambda_j}{\phi_i - \phi_j} \tag{3.1}$$

$$Intercept_{ij} = -(Slope_{ij} * \phi_i - \lambda_i) \tag{3.2}$$

$$Intersection_{ijkl} = \left[\frac{Intercept_{kl} - Intercept_{ij}}{Slope_{ij} - Slope_{kl}}, Slope_{ij} * \frac{Intercept_{kl} - Intercept_{ij}}{Slope_{ij} - Slope_{kl}} + Intercept_{ij}\right] \tag{3.3}$$

Once the arcs are created, the list of parameters in Table **??** are populated for each arc. For all arcs (i, j) if $j \in AR$, indicate TRUE for $Refueler_{ij}$ and if $j \in B$, indicate TRUE for $Base_{ij}$.

For each node $j \in AR$, the closest node $k \in B$ that can accommodate $Receiver_m$ is the missed refueling base used in the event of a failure during an air refueling at node j. $Fuel\_to\_MRB_{ij}$ is equal to $Fuel_{jk}$.

The distance along each arc is calculated as the great circle distance along the surface of the Earth. This is an approximation of the true distance and is consistent with the calculation. The calculation of the great circle distance along arc (i, j) uses the latitude and longitude of node i, ϕ_i and λ_i respectively, and node j, ϕ_j and λ_j respectively. Equation

Algorithm 1 Arc Creation

```
INPUT: Location Set with all associated names, types, latitudes, longitudes, and relationship to restricted zone
INPUT: Restricted Zone edge set with all associated starting and ending locations, types, and line equations
Set $Slope_{ij}$ = null
Set $Intercept_{ij}$ = null
Set $Intersection_{ijkl}$ = null
for Each Location pair $(i, j)$ where $j > i$ do
    Set $Intersect$ = FALSE
    Calculate $Slope_{ij}$ and $Intercept_{ij}$ using Equations 3.1 and 3.2
    for  Each Restricted Zone edge arc $(k, l)$ do
        Calculate $Intersection_{ijkl}$ using Equation 3.3
        if $Intersection_{ijkl}$ is between $i$ and $j$ along arc $(i, j)$ and between $k$ and $l$ along arc $(k, l)$ and $Type_{kl}$ = Restricted Zone then
            $Intersect$ = TRUE
        end if
    end for
    if $Intersect$ = TRUE or $i$ and $j$ are interior to restricted zone then
        Create arc with $Type_{ij}$ = Combat and associated parameters
    else
        Create arc with $Type_{ij}$ = Cruising and associated parameters
    end if
    Create arc $(j, i)$ with all parameters from arc $(i, j)$
end for
```

3.4 is used to calculate the angle in degrees between the two nodes then Equation 3.5 is used to find the distance between the nodes in nautical miles.

$$Angle_{ij} = \arccos(\cos(\phi_i) * \cos(\phi_j) * \cos(\lambda_j - \lambda_i) + \sin(\phi_i) * \sin(\phi_j)) \tag{3.4}$$

$$Dist_{ij} = Angle_{ij} * 60 \tag{3.5}$$

Some arcs in A can only be used in specific missions. These arcs cross the restricted zone and a portion of the arc is flown at combat speed ($Percent\_Combat_{ij}$). For all combat arcs created using Algorithm 1, $Percent\_Combat$ is calculated using the distance along the arc from the intersection with the arc in A^{RZ} (Equation 3.6).

If $Mission\_Type_m$ allows combat travel, all arcs are available for consideration. If $Mission\_Type_m$ does not allow combat travel, all arcs with $Type\_ij$ are removed from consideration.

$$Percent\_Combat_{ij} = \frac{GreatCircleDistance(Intersection_{ijkl}, Node_j)}{GreatCircleDistance(Node_i, Node_j)} \tag{3.6}$$

Before building the route for each $m \in M$, the fuel required for all arcs is calculated using the parameters in Table 3.3. The fuel required for the total time at target TaT_Fuel_m, is calculated using the same principle.

Table 3.3: Definitions of Mission Parameters Used in Calculating Fuel Requirements for Arcs

Parameter	Definition
$Receiver_m$	Receiver used in mission
TaT_Time_m	Total time spent at target
$Combat\_Speed$	Speed of receiver during combat
$Cruising\_Speed$	Speed of receiver while cruising
$Combat\_Fuel\_Flow$	Rate of fuel flow during combat
$Cruising\_Fuel\_Flow$	Rate of fuel flow while cruising
TaT_Fuel_Flow	Rate of fuel flow while at target

$$
\begin{aligned}
Fuel_{ij} = &\left(\frac{Percent\_Combat_{ij} * Dist_{ij}}{Combat\_Speed_m}\right) * Combat\_Fuel\_Flow_m \\
+ &\left(\frac{(1 - Percent\_Combat_{ij}) * Dist_{ij}}{Cruising\_Speed_m}\right) * Cruising\_Fuel\_Flow_m
\end{aligned}
\tag{3.7}
$$

$$
TaT\_Fuel_m = TaT\_Time_m * TaT\_Fuel\_Flow_m \tag{3.8}
$$

For all $(i, j) \in A$, Equation 3.7 is used to calculate the fuel required. The distance along arc (i, j) is split into Combat and Cruising portions. The rate of fuel flow and speed are based on the $Type_{ij}$ for each portion. Each portion is used to determine the amount of time required to travel from node i to node j based on the given speed (in nautical miles per hour). That time is then multiplied by the rate of fuel flow (in pounds of fuel per hour) to determine the number of pounds of fuel required for each arc. The total fuel required is the sum of the two portions of the distance.

IV. Methodology

Once the network is created, we need to find a route that connects the starting location to the mission target location and then to the landing base location.This project presents a greedy heuristic to find this route. The heuristic looks for a connection from the current location to the goal location ($Target_m$ or $Landing\_Base_m$) and considers the overall fuel required as each arc is added to the route. If the fuel drops below a level necessary for the mission to continue, the heuristic reroute the receiver to an air refueling location and resets the fuel remaining to the take off level.

We first present a framework of the heuristic then describe the detailed subroutines in Sections 4.2 to 4.4.

4.1 Framework

The algorithm starts at $TOBase_m$ and adds arcs and nodes until the route terminates at the landing location (Algorithm 2). The first goal of the algorithm is the $Target_m$. The Route Search (Algorithm 3) is used to determine which arc to next add to the route. This continues until $Target_m$ is reached.

Once $Target_m$ is reached, the Complete Time At Target (Algorithm 5) processes TaT_Time. After completing the TaT, the Route Search algorithm is used to route back to $Land\_Base_m$. Once $Land\_Base_m$ is reached, the mission is complete.

4.2 Route Search

The Route Search algorithm first searches for an arc (i, j) that directly connects the current location, i, and the input end location. If arc (i, j) exists, it becomes the next possible arc in the route. If there is no arc (i, j), the algorithm searches for the shortest two $(i, k)(k, j)$, three arc $(i, k)(k, l)(l, j)$, or four arc $(i, k)(k, l)(l, m)(m, j)$ path that connects the locations. The arc (i, k) becomes the next possible arc in the route. If no direct, two,

Algorithm 2 Framework

```
INPUT: Mission set with all associated starting locations, targets, and duties
INPUT: Network $G = (N, A)$ consisting of all bases, air refueling locations, and targets with required fuel for each connection
Set Mission_Complete = FALSE
Set Target_Reached = FALSE
for Each mission do
    Calculate all $Fuel_{ij}$ (Equation 3.7) and $TaT\_Fuel_m$ (Equation 3.8)
    while $Mission\_Complete$ = FALSE do
        if $Target\_Reached$ = FALSE then
            ROUTE = Call Route Search(goal = $Target_m$) to add arc to route
            if $Target_m$ is reached with this arc then
                ROUTE = Call Complete Mission (might require refueling during)
                $Target\_Reached$ = TRUE
            end if
        else
            ROUTE = Call Route Search(goal = $Land\_Base_m$) to add arc to route
            if $TOBase_m$ is reached with this arc then
                $Mission\_Complete$ = TRUE
            end if
        end if
    end while
    Output complete Route
end for
```

three, or four arc paths exist, the shortest arc (i, j) where i is the current location becomes the next possible arc in the route.

If there is enough fuel remaining to travel the next possible arc, the algorithm adds the arc to the route and reduces the associated fuel from the fuel remaining. If there is not, the Modify Existing Route adjusts the route to increase the fuel remaining by removing arcs from the route and rerouting the receiver to an air refueling location. Algorithm 4 outlines the Modify Existing Route.

4.3 Modify Existing Route

Modify Existing Route starts by removing the last arc in the route and adding the associated $Fuel_{ij}$ back into the remaining fuel. The current location is reset to node i

Algorithm 3 Route Search

```
INPUT: Network $G = (N, A)$ consisting of all bases, air refueling locations, and targets with required fuel for each connection
INPUT: Starting Location for next arc, $Start\_Loc$
INPUT: Current Goal, $Goal\_Loc$
INPUT: Current Route to Starting Location, $ROUTE$
INPUT: Current Fuel Amount, $Remaining\_Fuel$
Set $Arc\_to\_Add$ = null
if There exists an arc $(i, j)$ where $i = Start\_Loc$ and $j = Goal\_Loc$ then
    Set $Arc\_to\_Add$ equal to $(i, j)$
else if There exists a two arc path $(i, k)(k, j)$, three arc path $(i, k)(k, l)(l, j)$, or four arc path $(i, k)(k, l)(l, m)(m, j)$ where $i = Start\_Loc$ and $j = Goal\_Loc$ then
    Set $Arc\_to\_Add$ equal to the shortest $(i, k)$ that satisfies this condition
else
    Set $Arc\_to\_Add$ equal to the shortest $(i, k)$ in the network
end if
if There is sufficient fuel remaining to travel $Arc\_to\_Add$ then
    Add $Arc\_to\_Add$ to ROUTE
    Remove fuel to travel $Arc\_to\_Add$ from $Remaining\_Fuel$
else if There is sufficient fuel to travel to closest $AR$ then
    Add arc to closest $AR$
    Remove fuel to travel to $AR$ from $Remaining\_Fuel$
else
    $ROUTE$ = Call Modify Existing Route so $Remaining\_Fuel$ allows for arc to air refueling location
end if
Return $ROUTE$, $Remaining\_Fuel$
```

(starting node from arc removed) and the closest $k \in AR$ is identified. If there is enough fuel remaining to travel along the new arc (i, k) and arrive with enough fuel to divert to the missed refueling base in case of an aborted air refueling, the algorithm adds arc (i, k) to the route and decreases the remaining fuel by the associated $Fuel_{ik}$. If there is not enough fuel to add the new arc (i, k), the process is repeated, removing the last arc in the current route and searching for a feasible arc to a refueling location.

Algorithm 4 Modify Existing Route

```
INPUT: Network $G = (N, A)$ consisting of all bases, air refueling locations, and targets with required fuel for each connection
INPUT: Current Route, $ROUTE$
INPUT: Current Fuel Amount, $Remaining\_Fuel$
Set $Arc\_to\_Add$ = null
Set $Route\_Modified$ = FALSE
Set $Arc\_to\_Remove$ = null
Set $Current\_Loc$ = null
while $Route\_Modified$ = FALSE do
    Set $Arc\_to\_Remove$ = last arc in $ROUTE$
    Remove $Arc\_to\_Remove$ from $ROUTE$
    Set $Current\_Loc$ to beginning of $Arc\_to\_Remove$
    Increase $Remaining\_Fuel$ by the $Fuel_{ij}$ associated with $Arc\_to\_Remove$
    if There exists a one arc path $(i, j)$ where $i = Current\_Loc$ and $j \in AR$ then
        Set $Arc\_to\_Add$ equal to the shortest $(i, j)$ that satisfies this condition
    end if
    if There is sufficient fuel remaining to travel $Arc\_to\_Add$ then
        Add $Arc\_to\_Add$ to $ROUTE$
        Reset $Remaining\_Fuel$ to $TOFuel_m$ (from air refueling)
        Set $Route\_Modified$ = TRUE
    end if
end while
Return $ROUTE$, $Remaining\_Fuel$
```

4.4 Complete Time at Target

For some missions, the TaT is short enough to not require an air refueling. For others, the fuel remaining on arrival at $Target_m$, is insufficient to complete the TaT and an air refueling is required. Before traveling to the closest air refueling location $j \in AR$, as much of TaT_Time is completed as possible (Algorithm 5). The fuel to complete TaT_Time is reduced by the fuel left after traveling to the air refueling location ($TaT\_Fuel = TaT\_Fuel - (Remaining\_Fuel - Fuel_{ij} - Fuel\_to\_MRB_{ij} - Reserve\_Fuel_m)$) and arcs $(i, j)(j, i)$ added to the route (where $i = Target_m$). The remaining fuel is reset to $TOFuel_m$ and reduced by $Fuel_{ji}$. If there is now sufficient fuel to complete the TaT, the route is returned. If there is not, the next portion that can be completed is calculated and an additional air refueling is added to the route. This continues until the TaT_Time can be completed. The amount of time at target completed for each portion is calculated by dividing the fuel used for each portion by the TaT rate of fuel flow.

Algorithm 5 Complete Time at Target

```
INPUT: Network $G = (N, A)$ consisting of all bases, air refueling locations, and targets
  with required fuel for each connection
INPUT: Fuel Required for time at target, $TaT\_Fuel$
INPUT: Current Fuel Amount, $Remaining\_Fuel$
INPUT: Current Route, $ROUTE$
Set $TaT\_Complete$ = FALSE
Set $Arcs\_to\_Add$ = null
Set $Fuel\_to\_AR$ = null
Set $Arcs\_to\_Add$ equal to the shortest arc $(i, j)$ where $i$ = Target Location and $j \in AR$
Set $Fuel\_to\_AR$ equal to $Fuel_{ij}$ for arc $(i, j)$
while $TaT\_Complete$ = FALSE do
  if There is sufficient fuel to complete the TaT then
    $TaT\_Complete$ = TRUE
    Reduce $Remaining\_Fuel$ by $Remaining\_TaT\_Fuel$
  else
    Reduce $Remaining\_Fuel$ by ($Fuel\_to\_AR + Fuel\_To\_MRB + Reserve\_Fuel_m$)
    Reduce $TaT\_Fuel$ by $Remaining\_Fuel$
    Add $Arcs\_to\_Add$ to $ROUTE$
    Reset $Remaining\_Fuel$ to $TOFuel_m$
    Reduce $Remaining\_Fuel$ by $Fuel\_to\_AR$
  end if
end while
Return $ROUTE$, $Remaining\_Fuel$
```

V. Results and Analysis

After developing the methodology to create the routes, a set of sample missions was used to test the heuristic and compare the results to the routes generated by the current methodology used by HQ AMC.

5.1 Scenario Description

The scenario used to validate the methodology is a notional scenario developed by HQ AMC to enforce the no-fly zone in Syria. It consists of four types of missions: suppression of enemy defenses, defensive combat air patrol, pre-planned air interdiction, and Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnoissance (C4ISR). Each mission has a $TOBase_m$ and a $Target_m$ with an associated time at target (TaT). All missions have $Land\_Base_m = TOBase_m$ and return to $TOBase_m$ once the TaT is completed.

Table 5.1: Bases (B) and Targets (T) in Sample Scenario

Name	Abbreviation	Set
Fairfield	EGVA	B
Aviano	LIPA	B
Incirlik	LTAG	B
Med Carrier	CVMD	B
Cairo West	HECW	B
Sigonella	LICZ	B
Souda	LGSA	B
South Fighter Orbit	SFO	T
C4ISR West	C4ISRW	T
Damascus	DAM	T
Latakia	LAT	T
Navy Orbit	NO	T
North Fighter Orbit	NFO	T
C4ISR South	C4ISRS	T

The set of nodes N for the scenario consists of $|B| = 7$, $|T = 7|$, $|AR| = 7$, and $|N^{RZ}| = 23$. Table 5.1 shows the bases and targets. The 23 nodes in N^{RZ} are based on two surface to air missile (SAM) sites located in Syria and two no-fly zones over Lebanon and Israel. The SAM sites are located outside Latakia and Damascus and have a range of 100 nautical miles. Figure 5.1 shows all nodes and Figure 5.2 shows a close up of the area of the restricted zone.

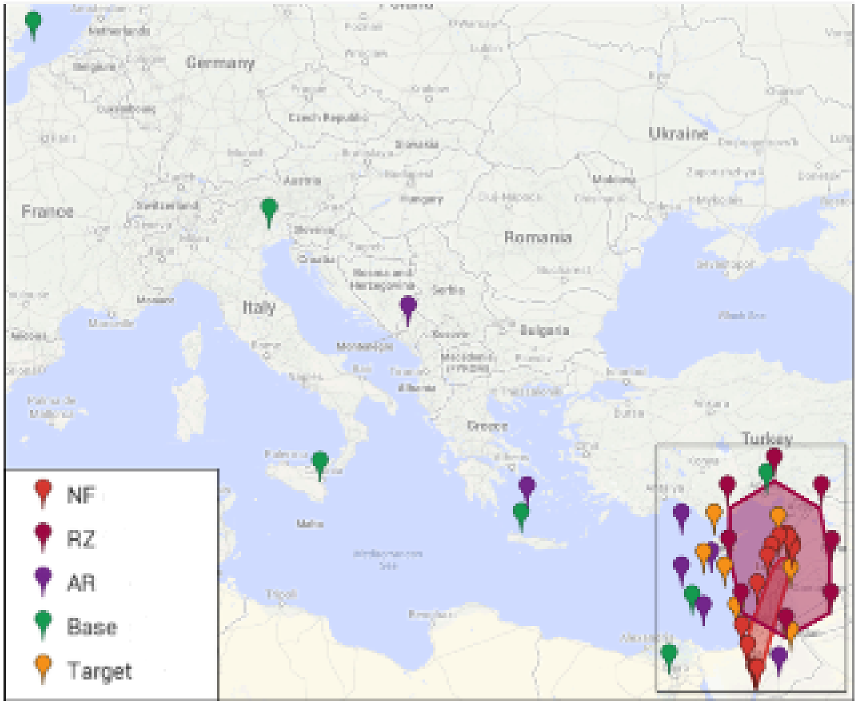

Figure 5.1: Map of Provided and Determined Network Nodes for Sample Scenario

The set of arcs A for the scenario consists of 965 arcs. There are 460 arcs with $Type_{ij}$ = Combat, 190 arcs with $Refueler_{ij}$ = TRUE, and 183 arcs with $Base_{ij}$ = TRUE. The distance along each arc ranges from 1 to 1,982 nautical miles.

The set of missions M consists of 10 missions (Table 5.2) provided by HQ AMC to test. Eight of the missions are unique. Two missions are identical but have a longer

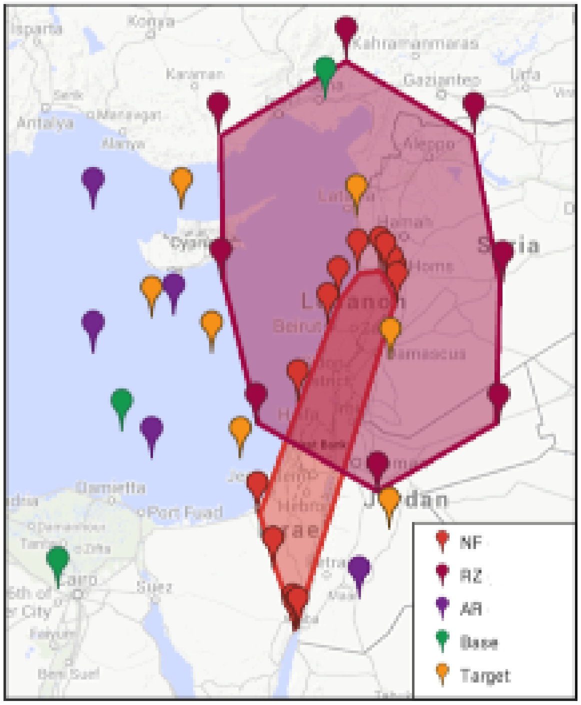

Figure 5.2: Close up of Network Nodes in Restricted Zone Vicinity

TaT. The two missions involving the restricted zone (Missions 1 and 2) are pre-planned air interdiction missions and have a short TaT (10 minutes). Only these two missions can use combat arcs. The other eight missions orbit at the target for 2- 12 hours and are not allowed to travel along combat arcs.

5.2 Results and Comparison to Current Method

Using the 10 missions provided by HQ AMC we compare the results of the heuristic to the methodology currently used by the decision maker. The quality of the solution is determined by the total fuel required by the route as compared to the HQ AMC method. The HQ AMC method was used to generate routes for the 10 mission profiles in the scenario. A comparison of the two methods, our Route Builder and the HQ AMC method, shows

Table 5.2: Mission Details for Sample Scenario

Mission	Take Off Location	Target	Time at Target
1	EGVA	DAM	10 minutes
2	LIPA	LAT	10 minutes
3	LTAG	SFO	4 hours
4	LTAG	NFO	4 hours
5	CVMD	NO	2 hours
6	HECW	NFO	4 hours
7	CVMD	NO	4 hours
8	LICZ	C4ISRW	8 hours
9	LICZ	C4ISRW	12 hours
10	LGSA	C4ISRS	8 hours

that the Route Builder is a faster method that provides routes that use less fuel or the same amount of fuel as the HQ AMC method.

5.2.1 Time Required.

The HQ AMC method requires 12 hours to process the network and build and verify the routes. Most of the method is done manually and involves transferring data between multiple tools for each stage of the construction.

Route Builder requires 1 hour to process the same network and mission set to create the set N^{RZ} from the provided restricted and no-fly zones and map the routes for verification. The majority of that time is spent determining the nodes and arcs around the threat and no-fly zones. The nodes can be reused for different scenarios that have the same restricted or no-fly zones to reduce the time required for future scenarios.

We capture the time needed to create the network and build the routes. The difference in time is shown in Table 5.3. The Route Builder algorithm runs in 10 seconds for the 10 mission profiles while the HQ AMC Method requires more than 11 hours to create the routes for the same 10 mission profiles (assuming the same amount of time is required to pre and post process the network).

Table 5.3: Time Required (in Seconds) for Each Route For Route Builder and HQ AMC Method

Mission	Route Builder	HQ AMC Method
1	4.9	3960
2	1.2	3960
3	1.1	3960
4	.2	3960
5	.2	3960
6	.3	3960
7	.2	3960
8	.6	3960
9	.6	3960
10	.4	3960

5.2.2 Route Comparison.

Table 5.4: Routes as Determined by Route Builder

Mission	Route
1	EVGA → AR9/10* → RZ5 → NF7 → NF6 → NF5 → DAM → NF5 → NF6 → NF7 → LAT → EVGA
2	LIPA → AR4* → LAT → AR7/8* → LIPA
3	LTAG → RZ5 → RZ6 → RZ7 → RZ8 → SFO → RZ1→ AR1* → NF2 → AR7/8 → RZ4 → LTAG
4	LTAG → RZ4 → NFO → RZ4 → LTAG
5	CVMD → NO → CVMD
6	HECW → NFO → HECW
7	CVMD → NO → CVMD
8	LICZ → C4ISRW → LICZ
9	LICZ → C4ISRW → LICZ
10	LGSA → C4ISRS → LGSA

Table 5.5: Routes as Determined by HQ AMC Method

Mission	Route
1	EVGA → AR10* → TP1 → DAM → TP1 → EVGA
2	LIPA → AR6* → LAT → AR5* → LIPA
3	LTAG → TP1 → TP2 → TP3 → AR2* → TP5 → SFO → TP5 → TP4 → TP3 → TP2 → TP1 → LTAG
4	LTAG → TP1 → TP2 → NFO → TP2 → TP1 → LTAG
5	CVMD → NO → CVMD
6	HECW → NFO → HECW
7	CVMD → NO → CVMD
8	LICZ → C4ISRW → LICZ
9	LICZ → C4ISRW → LICZ
10	LGSA → C4ISRS → LGSA

Table 5.4 shows the route determined for each mission using the Route Builder and Table 5.5 shows the routes as determined by the HQ AMC method. Any air refueling locations with a * indicates refueling occurs. Any air refueling location without a * did not refuel the aircraft. Table 5.6 shows the fuel required to fly the route to $Target_m$ and back to $Land\_Base_m$. It does not include the fuel required while at $Target_m$ or any air refuelings during the TaT.

Table 5.6: Fuel Required for Each Mission Excluding TaT_Fuel_m and Associated Air Refuelings

Number	Route Builder	HQ AMC	Difference
1	108,522	111,000	-2,478
2	58.940	63,760	-4,820
3	13,615	16,910	-3,295
4	3,525	3,800	-275
5	2,675	2,675	0
6	12,076	12,076	0
7	2,676	2,676	0
8	62,786	62,786	0
9	50,229	50,229	0
10	30,556	30,556	0

For Mission 1, the route determined by the route builder is shorter than the HQ AMC route due to a difference in the selection of air refueling location. The route for Mission 4 differs only by the selection of which restricted zone node to visit. For Missions 5-10, the two methods produced the same route. The Route Builder route for Mission 2 used less fuel due to a different choice of air refueling locations (Figure 5.3).

For Mission 3, the Route Builder route went to $Target_m$ around the restricted zone in the opposite direction of the HQ AMC route and utilized a different air refueling location (Figure 5.4). The green marker in each figure indicates the take off (and landing) base while the orange marker indicates the target. Purple markers show the air refueling locations visited in each route. The red zone marks the no-fly zone covering Israel and Lebanon while the blue zone marks the restricted zone covering the two SAM sites.

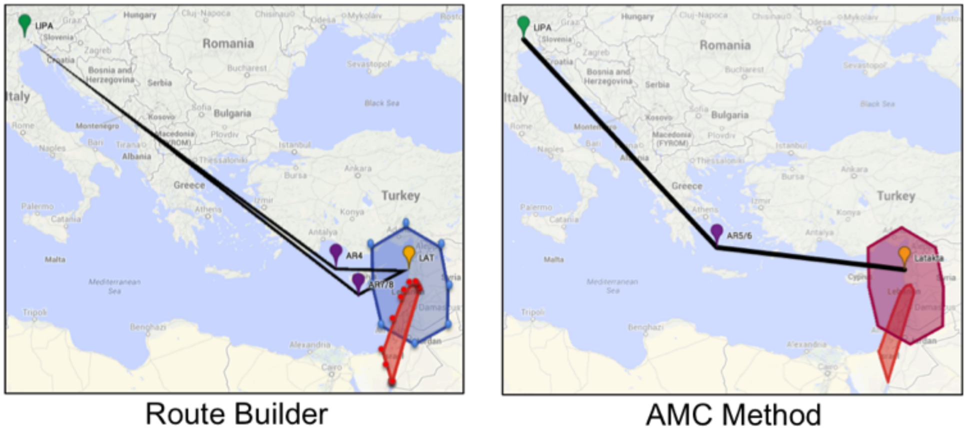

Figure 5.3: Map of Mission 2 Routes as Determined by Route Builder and HQ AMC Method

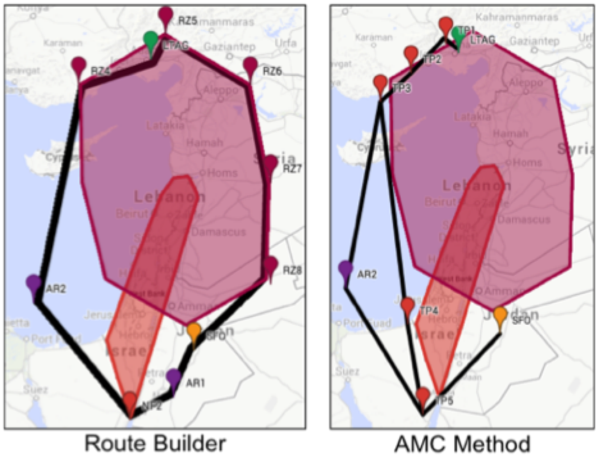

Figure 5.4: Map of Mission 3 Routes as Determined by Route Builder and HQ AMC Method

VI. Methodology Extensions

The methodology previously developed is used to determine the route with the least fuel cost. The secondary objective of minimizing fuel remaining to reduce the risk to the receiver at the landing base is met through post processing the results found using the greedy heuristic. Two methods to reduce the fuel remaining at the end of the mission are explored: shifting the TaT and reversing the route. Shifting the TaT can only be used for missions that have at least one refueling during TaT and reversing the route can only be applied to routes that start and end at the same location.

Seven of the ten missions examined have refuelings during their TaT. Table 6.1 shows the fuel remaining at the end of each mission with the current timing, the number of refueling during TaT, and the percentages completed between each refueling at the target.

Table 6.1: Fuel Remaining at Landing From Route Builder with Current TaT Portions

Mission	Fuel Remaining	Number of Refuelings	Percentages
3	882	3	17, 39, 39, 5
4	5,511	4	19, 23, 23, 23, 11
6	5,382	2	29, 42, 30
7	8,711	1	61, 39
8	36, 302	2	32, 58, 10
9	25,930	2	31, 48, 20
10	20,872	1	77, 23

The fuel remaining can be reduced by increasing the percent of the TaT completed after the last refueling by shifting time from the previous portion. For example, the receiver for Mission 3 refuels with 5% of the TaT to complete and departs the target with 10,139 pounds of fuel remaining. It only burns 9,257 pounds of fuel on the way back to the take off base leaving 882 pounds remaining. By shifting the 882 pounds from the third portion of the TaT to the last portion, the receiver departs the target with 9,257 pounds of fuel and arrives at the take off base with no remaining fuel. Table 6.2 shows the results after the shifting has occurred.

Table 6.2: Fuel Remaining at Landing From Route Builder with Shifted TaT Portions

Mission	Fuel Remaining	Number of Refuelings	Percentages
3	0	3	17, 39, *35, 8*
4	0	4	19, 23, 23, *1, 34*
6	0	2	29, *27, 45*
7	0	1	*25, 75*
8	0	2	32, *28, 40*
9	0	2	31, *31, 38*
10	0	1	*11, 89*

If the amount of fuel remaining at the end of the mission is larger than can be accommodated by shifting one portion, the amount remaining can be split up and each portion in the TaT can be reduced by the smaller amount. This shifts the remaining fuel out of each percentage and increases the final portion to reduce the remaining fuel upon landing.

Reversing the route is used when an air refueling occurs on the way back to the take off base and an air refueling did not occur on the way to the target. Each arc in the route is reversed and the order of the arcs is reversed. This moves the air refueling to earlier in the mission and reduces the remaining fuel.

Mission 2 can be modified to create a route that has an air refueling in the second half of the route by increasing the take off fuel by 10,000 pounds to 40,000 pounds (with a reserve of 4,000 pounds). This modified Mission 2 has the route: LIPA → LAT → AR7/8 → LIPA. The remaining fuel for this route is 13,982 pounds. By reversing the route to LIPA → AR7/8 → LAT → LIPA, the route ends with 8,086 pounds of fuel. By post processing our previous results, a route with the same fuel cost to get to and from the same target can land with less fuel remaining.

VII. Conclusions and Future Work

7.1 Conclusions

This project improved upon the current HQ AMC methodology used to find routes through a given network while maintaining necessary fuel levels. The focus of the methodology developed was to minimize the fuel used for the route and refuel as needed while maintaining operationally relevant details. The search technique used to determine the arcs to add to the route is a greedy approach that adds an arc with the approximate shortest overall connection to the goal location or the nearest air refueling location. By looking ahead to determine the total length of the connection to the goal, the search mimics the method used by an expert plotting the route manually. Further, the look ahead may allow the search to consider a longer arc due to the total length of the connection to the goal. This improves the search results and helps develop a route with fewer arcs.

The onboard fuel level was tracked as each arc was added to the route and the route modified if the level dropped below the given level. The route modification reroutes the receiver to the closest valid air refueling location to the receiver's current location or removes arcs from the route and searches for the closest valid refueling location to previous nodes in the route. Any rerouting to an air refueling location considered the fuel to divert to a missed refueling base in case of an aborted attempt at the location.

The greedy heuristic provides a quick, robust solution that seeks to minimize the fuel required for the route. The heuristic provides a solution in 8% of the time required by the current methodology and returns routes that use less fuel than those provided by the current methodlogy. The routes provided can be post processed to reduce the fuel remaining at the end of the route. The algorithm can handle multiple threat or no-fly zones and different mission types using different subsets of the arcs.

7.2 Future Research

7.2.1 Improving Current Algorithm.

Exact solution approaches for this problem should be explored to see if an optimal solution can be found quickly. The concepts in Kannon et al. [12], [13] require testing to determine scalability and could be used within the framework algorithm to improve results. Future research could also focus on modifying the heuristic to be less greedy.

7.2.2 Scheduling Multiple Missions.

Currently this problem examines one mission at a time. Each campaign is made up of many different missions over a period of time. Future research should examine the deconfliction of receiver routes and tanker utilization. Creating the route for each mission depending on the other missions being executed at the time of the mission would require deconflicting each node and arc in the network.

7.2.3 Optimizing Locations of Air Refuelers.

The location of the air refuelers is chosen manually by HQ AMC. These locations could be optimized to reduce fuel costs of routes that use the air refuelers as well as the cost to place the air refuelers in position. This would require knowledge of the routes using the air refuelers and may result in changes to those routes after the locations are optimized. The placement of the air refueling locations greatly impacts the fuel needed to complete each mission. Future work should collectively examine the placement of these locations in conjunction with building the routes.

Bibliography

[1] Ahuja, R. K., T. L. Magnanti, and J. B. Orlin (1993). *Network flows: Theory, algorithms, and applications*. Prentice-Hall, Englewood Cliffs, New Jersey.

[2] Barnhart, C., P. Belobaba, and A. R. Odoni (2003). Applications of operations research in the air transport industry. *Transportation Science 37*(4), 368–391.

[3] Barnhart, C., N. L. Boland, L. W. Clarke, E. L. Johnson, G. L. Nemhauser, and R. G. Shenoi (1998). Flight string models for aircraft fleeting and routing. *Transportation Science 32*(3), 208–220.

[4] Bartholomew-Biggs, M. C., S. C. Parkhurst, and S. P. Wilson (2002). Using direct to solve an aircraft routing problem. *Computational Optimization and Applications 21*(3), 311–323.

[5] Bartholomew-Biggs, M. C., S. C. Parkhurst, and S. P. Wilson (2003). Global optimization approaches to an aircraft routing problem. *European Journal of Operational Research 146*(2), 417–431.

[6] Bush, B. A. (2006, June 2006). *Analysis of fuel consumption for an aircraft deployment with multiple aerial refuelings*. Ph. D. thesis, North Carolina State University, Raleigh, NC. Available at: http://repository.lib.ncsu.edu/ir/bitstream/1840.16/3259/1/etd.pdf.

[7] Carlyle, W. M., J. O. Royset, and R. K. Wood (2009). Routing military aircraft with a constrained shortest-path algorithm. *Military Operations Research 14*(3), 31–52.

[8] Choi, J., J. Sellen, and C. Yap (1997). Approximate euclidean shortest path in 3-space. *International Journal of Computational Geometry and Applications 7*(4).

[9] Desaulniers, G., J. Desrosiers, Y. Dumas, M. M. Solomon, and F. Soumis (1997). Daily aircraft routing and scheduling. *Management Science 43*(6), 841–855.

[10] Harder, R. W., R. R. Hill, and J. T. Moore (2004). A java™ universal vehicle router for routing unmanned aerial vehicles. *International Transactions in Operational Research 11*(3), 259–275.

[11] Helgason, R. V., J. L. Kennington, and K. R. Lewis (2001). Cruise missile mission planning: A heuristic algorithm for automatic path generation. *Journal of Heuristics 7*, 473–494.

[12] Kannon, T. E., S. G. Nurre, B. J. Lunday, and R. R. Hill (2014a). The aircraft routing problem with refueling. Technical report, Air Force Institute of Technology.

[13] Kannon, T. E., S. G. Nurre, B. J. Lunday, and R. R. Hill (2014b). The aircraft routing with air refueling problem: Exact and greedy approaches. Technical report, Air Force Institute of Technology.

[14] Kinney, G. W., R. R. Hill, and J. T. Moore (2004). Devising a quick-running heuristic for an unmanned aerial vehicle (UAV) routing system. *Journal of the Operational Research Society 56*(7), 776–786.

[15] O'Rourke, K. P., W. B. Carlton, T. G. Bailey, and R. R. Hill (2001). Dynamic routing of unmanned aerial vehicles using reactive tabu search. *Military Operations Research 6*(1), 5–30.

[16] Papadimitriou, C. H. (1985). An algorithm for shortest-path motion in three dimensions. *Information Processing Letters 20*(5), 259–263.

[17] Pope, A. Bounding area in xy scatter chart. Accessed on 19 January 2014 at http://www.andypope.info/charts/convexhull.htm.

[18] Sundar, K. and S. Rathinam (2013). Algorithms for routing an unmanned aerial vehicle in the presence of refueling depots. Accessed on 19 January 2014 at http://arxiv.org/abs/1304.0494.

[19] United States Air Force (2012). *Air Force Doctrine Document 3-17: Air Mobility Operations - Airlift, Air Reserve Component, Air National Guard (ANG), Air Refueling, Aeromedical Evacuation, Maximum on Ground (MOG).* Progressive Management.

Appendix: Data

The Visual Basic for Applications code used in testing the methodology is available by contacting Dr. Sarah Nurre at AFIT. Tables 7.1 to 7.4 contain the data used in testing the methodology.

Table 7.1: Data for Network Nodes Provided

Name	Type	Latitude	Longitude
C4ISR South	Target	32.00	34.00
North Fighter Orbit	Target	35.50	33.00
Navy Orbit	Target	33.50	33.50
LTAG	Base	37.00	35.43
LIPA	Base	46.03	12.60
LICZ	Base	37.40	14.92
LGSA	Base	35.53	24.15
Latakta	Target	35.40	35.95
HECW	Base	30.12	30.92
EGVA	Base	51.68	1.79
Damascus	Target	33.42	36.52
CVMD	Base	32.40	32.00
C4ISR West	Target	34.00	32.50
South Fighter Orbit	Target	31.00	36.50
AR1	Air Refueling Location	30.00	36.00
AR2	Air Refueling Location	32.00	32.50
AR3	Air Refueling Location	33.50	31.50
AR4	Air Refueling Location	35.50	31.50
AR5/6	Air Refueling Location	36.48	24.43
AR7/8	Air Refueling Location	34.04	32.87
AR9/10	Air Refueling Location	42.84	18.98

Table 7.2: Data for Missed Refueling Bases Provided

Base	Aircraft Suitability
EGVA	B2 E3 EC130 F15C F15E F16CJ nEA18G nF18E RC135
CVMD	nEA18G nF18E
HECW	E3 EC130 F15C F15E F16CJ nEA18G nF18E RC135
LGSA	E3 EC130 F15C F15E F16CJ nEA18G nF18E RC135
LICZ	E3 EC130 F15C F15E F16CJ nEA18G nF18E RC135
LIPA	E3 EC130 F15C F15E F16CJ nEA18G nF18E RC135
LTAG	E3 EC130 F15C F15E F16CJ nEA18G nF18E RC135

Table 7.3: Data for Threat Zones Provided

Threat Zone	Radius	Center Latitude	Center Longitude
SA-5 North	100NM	35.55	35.77
SA-5 South	100NM	33.24	36.19

Table 7.4: Data for Missions Provided

Mission Number	Aircraft	Type	Take Off Base	Target	Landing Base	Duty Time	Take Off Fuel	Reserve Fuel	Cruising Speed	Cruising Fuel Flow	Orbit Speed	Orbit Fuel Flow	Combat Speed	Combat Fuel Flow
1	B2	PAI	EGVA	Damascus	EGVA	0.1667	130,000	30,000	420	12,000	400	10,000	400	10,000
2	F15E	PAI	LIPA	Latakta	LIPA	0.1667	35,000	3,500	450	10,000	480	12,000	48	12,000
3	F16CJ	SEAD	LTAG	South Fighter Orbit	LTAG	4	12,000	1,200	450	5,000	480	6,000	480	6,000
4	F16CJ	SEAD	LTAG	North Fighter Orbit	LTAG	4	12,000	1,200	450	5,000	480	6,000	480	6,000
5	NF18E	DCAP	CVMD	Navy Orbit	CVMD	2	24,000	4,000	450	6,000	450	6,000	450	6,000
6	NF15C	DCAP	HECW	North Fighter Orbit	HECW	4	24,000	4,000	450	6,000	450	6,000	450	6,000
7	NEA18G	SEAD	CVMD	Navy Orbit	Navy Orbit	4	24,000	4,000	450	6,000	450	6,000	450	6,000
8	E3	C4ISR	LICZ	C4ISR West	LICZ	8	100,000	20,000	420	15,000	420	15,000	420	15,000
9	RC135	C4ISR	LICZ	C4ISR West	LICZ	12	100,000	20,000	420	12,000	420	12,000	420	12,000
10	EC130	C4ISR	LGSA	C4ISR South	LGSA	8	50,000	5,000	220	6,000	200	4,000	200	4,000

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704–0188*

1. REPORT DATE *(DD–MM–YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From — To)*
27–03–2014	Master's Thesis	Oct 2012–Mar 2014

4. TITLE AND SUBTITLE Improving the Air Mobility Command's Air Refueler Route Building Capabilities	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Kannon, Tanya E., Captain, USAF	**5d. PROJECT NUMBER** JON 13S141 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB, OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENS-14-M-14
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) United States Transportation Command Joint Distribution Process Analysis Center Attn: Pat Mcleod 508 Scott Drive DSN: 770-5238 Scott Air Force Base, IL 62225-5357 patrick.k.mcleod.civ@mail.mil	**10. SPONSOR/MONITOR'S ACRONYM(S)** USTRANSCOM/TCAC **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

We consider the problem of routing an aircraft (receiver) from a starting location to a target and back to an ending location while maintaining a fuel level above a predetermined level during all stages of the route and avoiding threat and no-fly zones. The receiver is routed to air refueling locations to refuel as required. The development of the network requires the processing of threat and no-fly zones to create the set of nodes that includes the bases (starting and end locations), the targets, and air refueling locations in addition to the restricted zone nodes. We develop a greedy heuristic that builds the route using arc paths and the on board fuel level to determine the termination of each sequential arc path. Post processing of the routes reduces the fuel remaining on board by shifting the time at target or reversing the route. The results from the greedy heuristic are compared to the results from the current methodology and show that the heuristic requires less time to produce routes that require less fuel.

15. SUBJECT TERMS

Air Refueling, Heuristic, Route Building

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. Sarah G. Nurre (ENS)
U	U	U	UU	46	**19b. TELEPHONE NUMBER** *(include area code)* (937) 255-3636 x4319 Sarah.Nurre@afit.edu